LCA Case Studies

Environmental Life Cycle Assessment of Linoleum

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Abstract. Linoleum is a floor covering consisting mainly of linseed oil, other vegetable oils, wood flour and limestone on a carrier of jute. Forbo-Krommenie B.V. commissioned the Centre of Environmental Science (CML) to carry out an Environmental Life Cycle Assessment for linoleum floors. The goal of this study was to assess the environmental performance of linoleum floors, indicating possible options for improvement, and assessing the sensitivity of the results to methodological choices. The functional unit was defined as: 2000 m² linoleum produced in 1998, used in an office or public building over a period of 20 years. The method followed in this study is based on a nearly final draft version of the LCA guide published by CML in corporation with many others, which is an update of the guide on LCA of 1992.

From the contribution analysis, the main contributing processes became clear. In addition, the sensitivity analysis by scenarios showed that the type of maintenance during use and the pigments used can have a large influence on the results. Major data gaps of the study were capital goods and unknown chemicals. Sensitivity analysis also showed that these gaps can lead to an underestimation. Based on this study, some options to improve the environmental performance of linoleum were formulated and advice for further LCA studies on linoleum was given.

Keywords: Case studies; environmental performance, improvement options; floor coverings; Life Cycle Assessment (LCA); linoleum; scenarios; sensitivity analysis

Introduction

Linoleum is a floor covering consisting of a binder made from linseed oil and/or vegetable drying oils and rosin mixed with wood flour and/or cork, inorganic filler and pigments, on a carrier of jute. Forbo-Krommenie B.V. (Forbo), the world's largest producer of linoleum floor covering, commissioned the Centre of Environmental Science (CML) to carry out an Environmental Life Cycle Assessment (LCA) in order to assess the environmental performance of linoleum floors, to indicate possible options for improvement, and to assess the sensitivity of the results for methodological choices. Although earlier work on linoleum floor coverings was done by Potting and Blok (1995), Jönsson et al. (1995) and Günther and Langowski (1997), these studies were based on less detailed information on linoleum production, maintenance and production of raw materials and maintenance products. Moreover, most data in these studies was not provided by Forbo directly and therefore, in some cases, not realistic. Therefore, they could not be used for this goal. These studies are discussed further in the interpretation phase.

The method followed in this study is based on a nearly final draft version by Guinée et al. (2000)[1] which represents an update of the CML guide on LCA by Heijungs et al. (1992). For a detailed description of this method, we refer to Guinée et al. (2000) and, for a discussion on the differences between the old and the new guide, to Guinée (2001) and Guinée et al. (2001). This update follows the ISO standards and guidelines as closely as possible, providing an operational outline of the theoretical starting points, requirements and guidelines given in the different ISO documents on LCA (a.o. ISO 14040, 14041, 14042 and 14043). For CML, this case study offered an opportunity to 'test' the updated guide. A peer review was carried out according to ISO 14040 by Elin Eriksson of Chalmers Industriteknik[2]. This article follows the reporting guidelines of Guinée et al. (2000). Therefore, the structure of this article follows the successive phases of an LCA rather than the more traditional structure of research articles.

1 Goal and Scope

The goal of this LCA study was to gain insight into:

- The environmental impact of linoleum floor coverings.
- The effects of the different processes in the life cycle chain on the environmental impact of linoleum.
- Possible improvement options.
- The effects of choices in methods and data on the outcomes.

The following **functional unit** was used as a basis for this study: 2000 m² linoleum produced in 1998 and used in an office or public building over a period of 20 years and its subsequent disposal.

Different functionally equivalent alternative systems were considered. The baseline system was: The production (in 1998), laying, use and maintenance of 2000 m² 2.5 mm Marmoleum®[3], in an office or public building in the Nether-

[1] The final version of Guinée et al. slightly differs from the draft version used for this study.

[2] The report of the full study can be obtained by writing to: CML Library, P.O. Box 9518, 2300 RA Leiden, The Netherlands, or by E-mailing to eroos@cml.leidenuniv.nl, mentioning the report no. CML report 151. The report can also be downloaded from the web site: http://www.leidenuniv.nl/interfac/cml/ssp/publications/index.html

[3] Forbo produces various types of linoleum which differ in ingredients, ratio between these ingredients and fabrication process.

lands, over a period of 20 years and its subsequent disposal. The 'technical' life span of linoleum floors is longer than 20 years, but because floors are often removed because of aesthetic reasons or renovation, the actual life span in public building is 20 years on average (information provided by Forbo). In addition to the baseline system, a number of scenarios was examined as sensitivity analysis.

2 Inventory

2.1 Process tree

The process tree for the baseline system is given in **Fig. 1**.

2.2 System boundaries

System boundaries were treated according to Guinée et al. (2000). Three types of boundaries are distinguished. Those between:

1. The product system and the environment,
2. included and disregarded processes ('cut-off'),
3. the product system under investigation and other product systems.

Boundaries between product system and environment play an important role for two types of processes in this study, namely landfill processes and agricultural processes. Landfilling is treated as an economic process with long-term inputs and emissions. The agricultural soil and the portion of the crop that is not harvested are considered to be environment. In this study therefore, applied pesticides are treated as direct emissions to soil, water and air. Added N and P fertilisers are understood as being emissions to the environment in as far as the amount of N and P added is not harvested.

Boundaries between included and disregarded processes play a role in the decision about exclusion of capital goods. The production of capital goods is not included in this study. It is very difficult to get a good estimate of the production of capital goods that may be associated with one unit of product (linoleum). In the sensitivity analysis, the effect of including a rough estimation of capital goods is analysed.

Boundaries between the product system under investigation and other product systems play a role when processes produce more than one product, or process more than one type of waste. In this case, allocation of the inputs and outputs of this process should take place. Allocation occurred for the following processes:

- The sawing of raw wood for other use (products: production wood and wood remainders).
- The production of linseed oil (products: linseed oil and linseed expellers).
- The transport, spinning and weaving of jute (products: jute and re-usable jute waste).
- The extraction of rosin from raw rosin (products: rosin and turpentine)
- The incineration of linoleum (one service: waste handling; one product: energy)
- The production of tall oil and paper (products: tall oil and paper)

All processes were allocated according to the guidelines of Guinée et al. (2000), which conform with ISO. This means

Fig. 1a

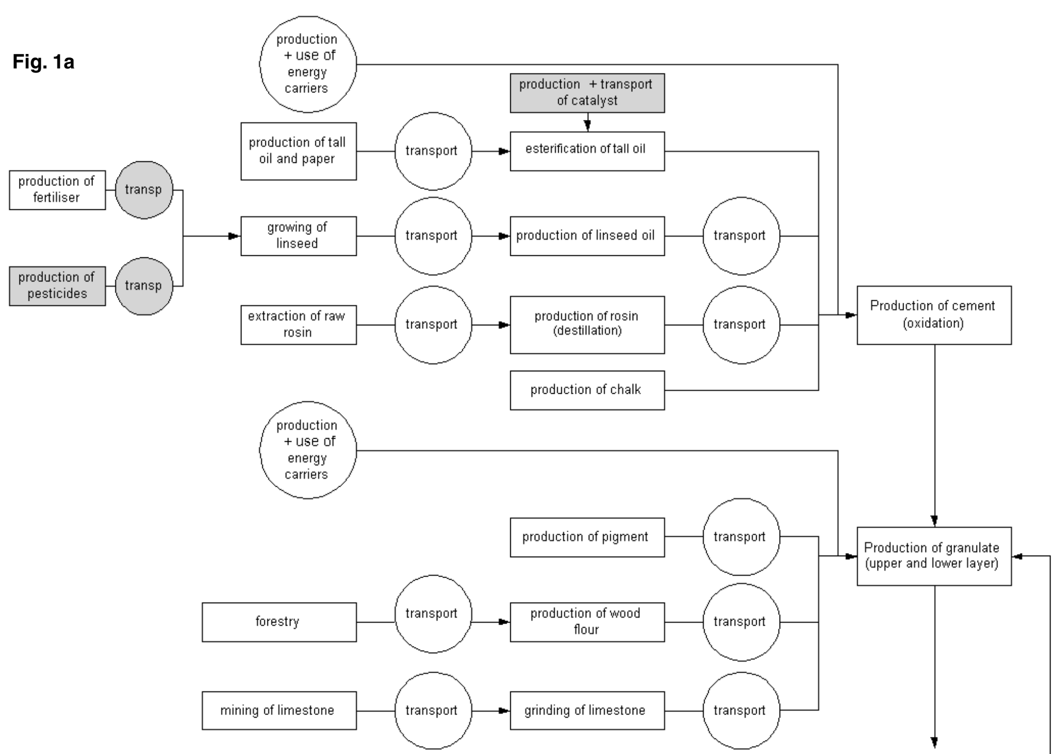
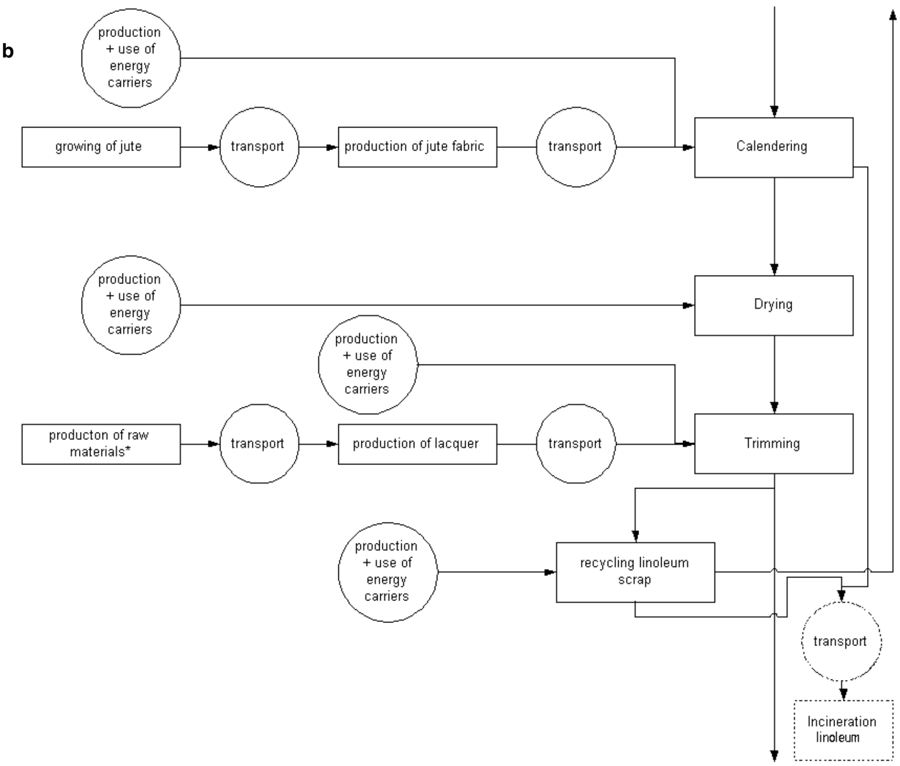


Fig. 1: Process tree for the use and disposal of linoleum floors. The production of capital goods is excluded from the system.

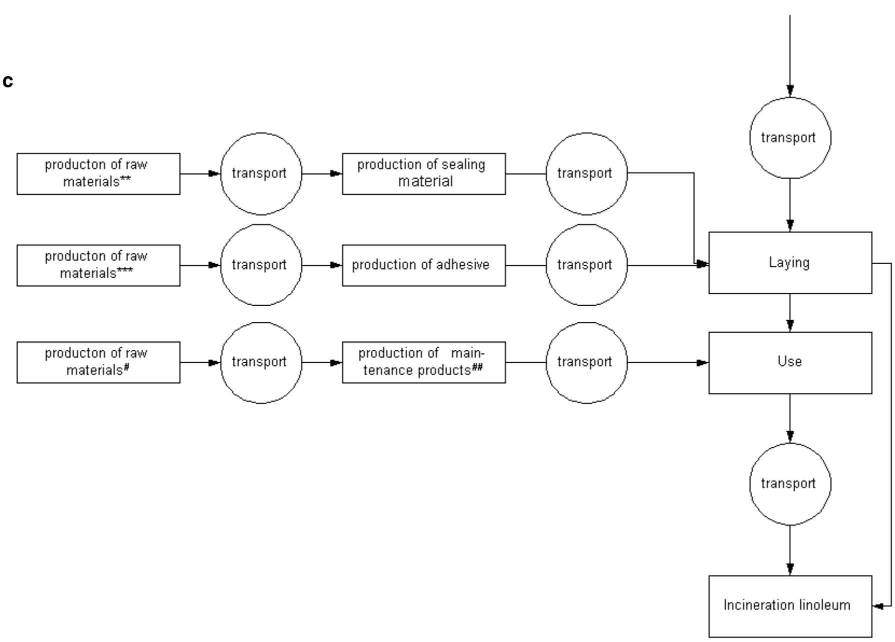
a) Grey fill: no data available for this process, no data on this process included in the baseline system (see sensitivity analysis on data gaps)

Fig. 1b



b) Dashed lines (incinerating linoleum): Process copied from other page, duplicate.
*: Information on the production and transportation distance of 96% of the raw materials was available, information on the production of ingredients for these raw materials was also partly available (= energy use, transport and waste during production of these ingredients was available, no information available on the production of ingredients for the ingredients see appendix A)

Fig. 1c



c) **: Information on the production and transportation distance of none of the raw materials was available, information on the production and transportation distance of 50% of the ingredients for the raw materials was available (rosin), information on the production of other ingredients and information on energy use, etc for the production of the raw materials was not available (see appendix A).
***: Information on the production and transportation distance of 98% of the raw materials was available, information on the production of ingredients for these raw materials was also available in part (information on gum and limestone, as well as on energy use, transport and waste during production of some other ingredients and ingredients for these ingredients are unknown, see appendix A).
#: Information on production and transport of maintenance products for the Dutch scenario is available for all products with the exception of a product used to remove the polymer top layer of linoleum flooring. No information is available on the transport of maintenance products for the Swedish scenario
##: Information on the raw material production of Dutch maintenance products is not complete, information on the raw material production of Swedish maintenance products is fragmented.

using economic allocation where possible and substitution with cradle-to-gate data for processes where this is less feasible. Almost all processes were allocated based on the economic value of the co-products. The exception to this is the process of 'incineration of linoleum' in which the substitution method was used. The produced energy was substituted by avoided electricity use.

Sometimes also geographical boundaries and boundaries in time are discerned. There are no geographical boundaries for this study, as the raw materials for linoleum are produced all over the world and linoleum is sold all over the world. As to boundaries in time: We used the most recent data available for all processes, mostly data from 1998.

2.3 Data gathering

Data on production, laying and maintenance were provided by Forbo. The maintenance of the floor, and thus the amount of maintenance products used, is based on the maintenance sequence for public buildings in the Netherlands as advised by Forbo (**Table 1**). Data on production, transportation and use of raw materials and maintenance products were provided by suppliers from Forbo. Data on more general 'background' processes such as transportation, energy production and landfill where gathered from ETH 1996. Data on a few specific processes such as the incineration of linoleum, the production of detergents and the production of fertilisers were gathered from specific LCA case studies or inventory studies. Since the complete data file is very long, it is not provided here. More information and references on the data used can be downloaded from the CML web site[4].

2.4 Description of data quality

Data quality can be described by validity (representativeness) and reliability (completeness, variability and uncertainty). The quality of the data collected is described in these terms below.

Most data on the production of raw materials is representative for the specific processes, but reliability is not known, since most of this data is not validated. Especially the data provided by suppliers of Forbo differ largely in completeness. Data on the processes which take place at the factory site of Forbo is representative, more completely and probably more reliably than that on the production of raw materials. The total amount of VOC emitted at the factory site was provided by Forbo, but the exact composition is not known. Therefore, the composition was estimated based on UK emission profiles (Derwent et al. 1998) as advised by Guinée et al. (2000). However, this profile proved to be not very representative (see paragraph interpretation for further discussion). The data on the incineration of linoleum is representative and seems complete. However, the assumption that electricity is produced with 40% efficiency might be somewhat high. The ETH data is probably representative and reliable for the energy data. The ETH data on transportation processes, landfill processes and other processes is probably less representative for the case.

2.5 Data gaps

No process data was available for the following processes (see also Fig. 1):

- The production and transport of pesticides (use and emission of pesticides are included).
- The production and transport of one maintenance product, of some raw materials needed for other maintenance products (additives, thickeners, solvents) and almost all ingredients for those raw materials.
- The production and transport of some raw materials needed for the production of materials used during laying (adhesives and materials used to seal the seams of professionally used linoleum floors)
- The production and transport of the catalyst needed during linoleum production
- The production and transport of the fertiliser S needed in the process of 'growing linseed'.

In the sensitivity analysis, the effect of including a rough estimation for the production and transport of these chemicals is analysed.

[4] http://www.leidenuniv.nl/interfac/cml/ssp/publications/index.html (CML-report 151 + appendices; these appendices also include a complete intervention table of the baseline system).

Table 1: Maintenance sequence for linoleum floors in public buildings in the Netherlands

Activity	Frequency in 20 years	Maintenance product used per turn per m^2
First cleaning	1	0.16 l water $1.3 \cdot 10^{-3}$ l cleaner $2.0 \cdot 10^{-2}$ l sealer
Dust wiping	5200	$5.0 \cdot 10^{-3}$ wiping cloth
Spot cleaning	5200	$1.7 \cdot 10^{-4}$ l cleaner $2.0 \cdot 10^{-2}$ l water
Spot spaying	260	$1.0 \cdot 10^{-3}$ l spray
Stripping and resealing	6	$2.0 \cdot 10^{-2}$ l stripper $4.0 \cdot 10^{-2}$ l sealer

3 Impact Assessment

3.1 Impact categories and impact assessment methods

The impact categories included in this study are presented in **Fig. 2** and **3**. This set is based on the baseline impact categories of Guinée et al. (2000)[5]. 'Odour' is added to this list because of its importance to linoleum production. Because of the emissions of specific VOC while producing linoleum, a very specific odour can be smelled at the production site.

The impact assessment was carried out conformable to a nearly final draft version of Guineé et al. (2000). Characterisation and normalisation factors used are in some cases different from the ones published in the final version of Guinée et al. (2000).

[5] The discussions on the baseline impact categories for Guinée et al. (2000) were not finalised the moment this study was carried out. Therefore, the selection here differs from the advice in the final version of Guinée et al. (2000): Land use is not included and eco-toxicity has different subcategories than in Guinée et al. (2001).

3.2 Flows not assigned to an impact category

In total there were 264 inputs/outputs that could not be assigned to an impact category. These are mainly from the ETH database. A large portion of the emissions (132 emissions) are radioactive emissions. Since radiation is not included in this study (see selected impact categories), they were not included in the impact assessment results.

4 Interpretation

4.1 Contribution analysis

Fig. 2 shows the contribution of life cycle stages (in %) to the category results. In this figure, the total of all 'positive' contributions is set at 100%, neglecting the negative contri-

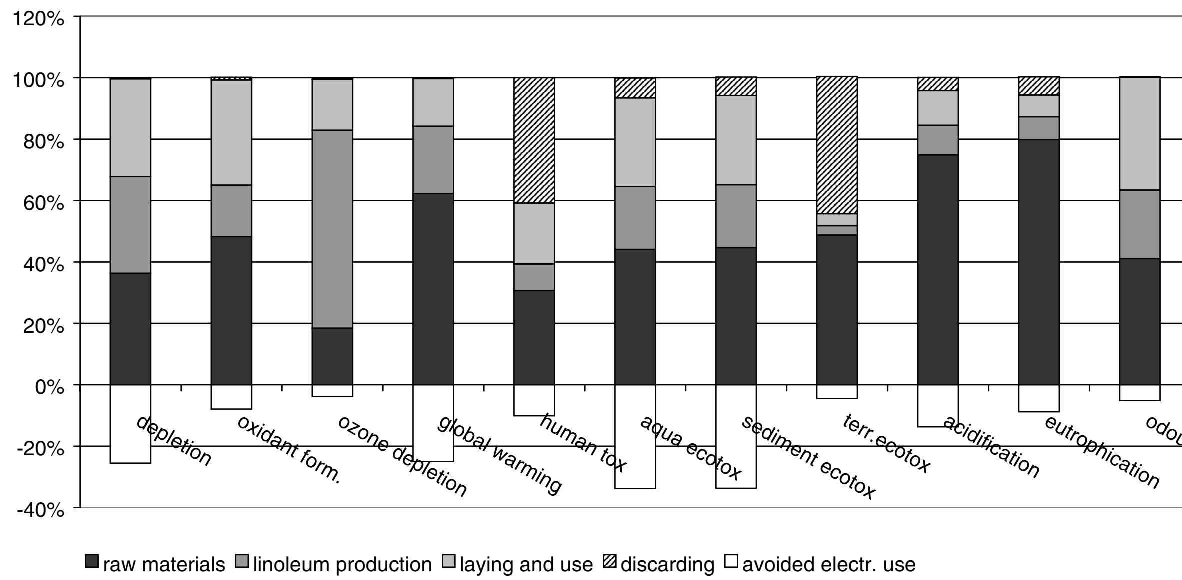


Fig. 2: The contribution of life cycle stages to the category results

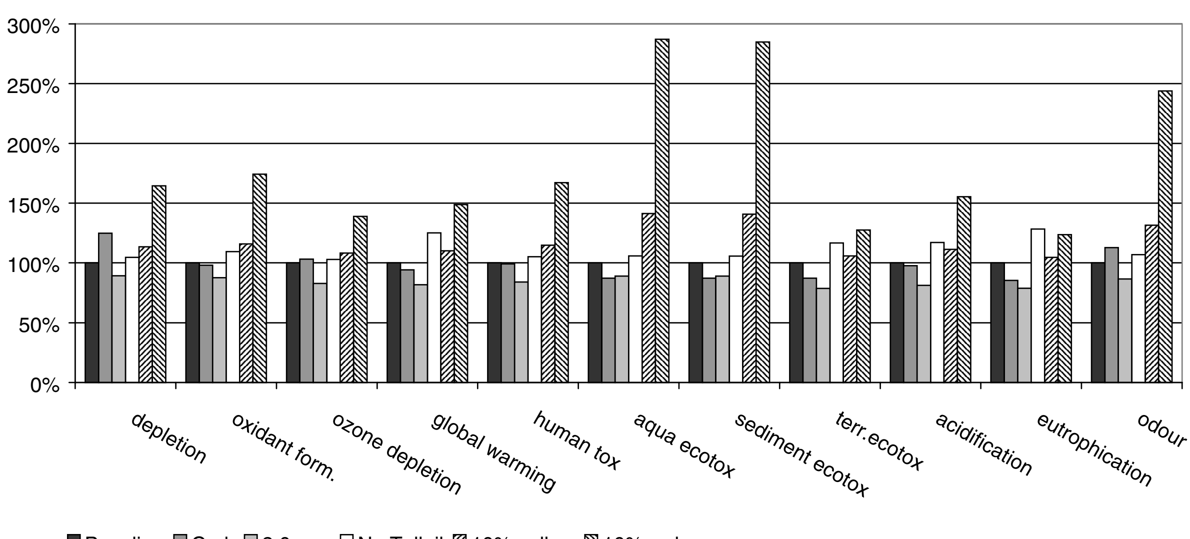


Fig. 3: Environmental profile for the baseline system and five alternative scenarios related to differences in ingredients

Table 2: Processes contributing 10% or more to more than one impact category

Process	Impact categories to which the process contributes at least 10%	%*	Mainly caused by	%*
The growing of linseed				
	eutrophication	53	NH_3	53
	terrestrial ecotoxicity	37	pesticides	37
	global warming	37	N_2O	37
	acidification	28	NH_3	28
	odour	13	NH_3	13
Gas and electricity use at Forbo-Krommenie B.V.				
	abiotic depletion	32	natural gas	28
	global warming	21	CO_2	21
	aquatic ecotoxicity (only electricity)	20	heavy metals (mainly barium and vanadium)	18
	sediment ecotoxicity (only electricity)	19	heavy metals (mainly barium and vanadium)	19
	odour (only gas)	18	H_2S	17
Oil used for the production of maintenance products				
	photo. oxidant formation	27	VOC-mix**	27
	abiotic depletion	13	crude oil	13
	human toxicity	11	VOC-mix**	11
Transportation of raw materials				
	oxidant formation	25	VOC-mix**	25
	sediment ecotoxicity (only freighter)	10	heavy metals (mainly vanadium)	10
	human	10	VOC-mix*	10
	acidification	15	SO_2	9
Incineration of linoleum				
	terrestrial ecotoxicity	44	heavy metals (mainly mercury)	44
	human toxicity	40	heavy metals (mainly cadmium and arsenic)	39
Coal used for the production of detergents and acrylic dispersions/ emulsions				
	odour	21	H_2S	21
	aquatic ecotoxicity	12	heavy metals (mainly barium and vanadium)	12
	sediment ecotoxicity	12	heavy metals (mainly barium and vanadium)	12

*: % = percentage of total result for the given impact category

**: VOC emissions are usually given as a total the VOC-mix. However, for the impact assessment, individual substances are needed. A standard emission profile representative for stationary combustion is used to estimate which individual substances are present in this mix.

bution of energy production while burning linoleum. These 'negative' or 'avoided' emissions and extractions are also shown in Fig. 2 where they are expressed as a percentage of the total positive contribution. From this figure, it can be seen that the stage 'production of raw materials' contributes the most to almost every impact category.

Only a limited number of processes are responsible for the highest contributions to most impact categories. In **Table 2**, these main contributing processes are viewed in detail. The total of all positive contributions is again set at 100% (the 'avoided' emissions and extractions are not included in this table). From the last column in Table 2, it can be seen that a limited set of emissions is responsible for the high contribution of these processes.

The results for 'odour' and 'depletion of the ozone layer' should be considered with care, since the emission of individual substances had to be estimated from the group parameter 'total VOC emission' using a standard emission profile as advised by Guinée et al. (2000). The results of the contribution analysis shows that this estimate probably does not match the real VOC mix very closely, since the special 'odour' at the linoleum production site caused by emissions of VOC is in reality more important than H_2S caused odour, which is the main cause of 'odour' at the production site in this study. We may therefore conclude that 'odour' is probably underestimated by using this standard emission profile. The results for 'depletion of the ozone layer' are probably overestimated because of the use of this standard emission profile. In this study, 62% of the ozone depletion is caused by VOC-emissions from the production site. This is entirely the result of the emission of 1,1,1-trichlorethane. This is a solvent which is part of the standard emission profile, but which is not used at the production site. This shows us that conversions from group parameters with standard emission profiles should be carefully considered in the interpretation phase.

4.2 Comparison with previous LCA-studies on linoleum (consistency check)

Earlier work on linoleum floor coverings was done by Potting and Blok (1995), Jönsson et al. (1995) and Günther and Langowski (1997). Of these, only the first is detailed enough to make a proper comparison. The results of Potting and Blok (1995) show a much heavier contribution of the phase 'production of linoleum'. This is the main contributor to abiotic depletion, oxidant formation and global warming. The higher contribution of the other stages in our study of 'raw material production' and 'laying and use' can be explained by two factors:

- More data was compiled here on life cycle stages other than the production of linoleum, such as raw material production, and use and maintenance. Two examples of additional data are mentioned here. First, we included NH_3 and N_2O emissions which occur during the growing of linseed, resulting in a relative high contribution of this process to acidification and global warming. Second, we did take into account not only the maintenance of the floor itself but also the production of the maintenance products (and their ingredients if possible), resulting in a considerably higher contribution of this stage, for instance, to abiotic depletion and photochemical oxidant formation as compared to other studies. However, parts of the additional data we used were not validated or made public.
- We used actual emission data from the factory site directly provided by Forbo. These values were lower than the values from the environmental permit which were used in the other studies, because of the improvements made by Forbo after the submission of the permit. The lower values are more realistic. This data is amongst others published in environmental reports and in reports by Central Statistics Netherlands.

Sensitivity analysis using scenarios

In the sensitivity analysis, various scenarios have been analysed:

1. Alternative countries of use: Sweden and USA. This includes different transportation distances, but also differences in the product and maintenance system.
2. Alternative products/ingredients: Linoleum with cork as a filler instead of wood chips, a thinner linoleum layer (2.0 mm), using only linseed oil instead of partly tall oil and using other pigments (yellow and red) besides TiO_2.
3. Alternative allocation methods/waste treatment: Substituting the energy produced by gas production instead of electricity, no substitution, dumping linoleum waste instead of incineration.
4. Alternative data including: Variations in pesticide and fertiliser use and in transportation distance of the linoleum by freighter.
5. Adding an estimation for missing processes. Main data gaps in the study are capital goods and chemicals. The estimation of production of capital goods was based on the input/output data on 'general industrial machinery and equipment' from the Carnegy Mellon web site: http://www.eiolca.net. Emissions of toxic substances could not be derived from this database. The estimation of production of chemicals was based on 'organic chemical' in the ETH (1996) database.

Not all results of these scenarios are presented here. In Fig. 3, the results for alternative products and ingredients are compared to the baseline system (scenario study number 2). The category results for the baseline system are all scaled to 100%. From this figure, it can be seen that:

- Using cork instead of wood shows lower results for most impact categories but higher results for abiotic depletion (25% higher), depletion of the ozone layer (3% higher) and odour (13% higher); this is mainly a result of gas use during the milling and drying of cork;
- the thinner linoleum layer shows a 15% lower result on average for all impact categories;
- linoleum without tall oil shows a 15% higher result on average for all impact categories;
- the use of other pigments can result in a considerable increase for some impact categories; we found that replacing 10% of the TiO_2 by red pigment can increase the result for many impact categories with more than 50%, for aquatic toxicity the result was even more than 200% higher.

In **Table 3**, the scenarios including estimations for data gaps are presented (scenario study number 5). The percentages are again relative to the baseline system. Data gaps may

Table 3: Environmental profile for the baseline system, including estimates for capital goods and missing chemicals, relative to the baseline system without these estimates (in %)

	Addition of missing chemicals	Addition of capital goods	Addition of missing chemicals and capital goods
Depletion of abiotic resources	114%	105%	118%
Photochem. oxidant formation	113%	107%	119%
Depletion of the ozone layer	107%	102%	109%
Global warming	112%	110%	122%
Human toxicity	110%	103%	113%
Aquatic ecotoxicity	138%	100%*	138%
Sediment ecotoxicity	138%	100%*	138%
Terrestrial ecotoxicity	106%	100%*	106%
Acidification	116%	106%	122%
Eutrophication	104%	104%	108%
Odour	105%	101%	105%

*: no useful data on toxic emissions resulting form the production of capital goods available

lead to an underestimation of up to 40%. The consequences of this possible large influence of data gaps will be discussed later in this article.

5 Discussion and Conclusions

5.1 Improvement options

Various improvement options can be considered based on the results of the contribution analysis and the various scenarios described above. Below, they are discussed per production stage.

In the stage 'production of raw materials' the process 'growing of linseed' is a very important process as was shown in the contribution analysis (Table 2). The data for this process depend largely on assumptions. If these assumptions are not realistic, this may have large influences on results. Therefore, it is advisable to try to ground these assumptions with better data. Still, using linseed that is cultivated with less fertiliser and less pesticide would probably greatly improve the environmental profile for linoleum produced by Forbo. Reduction in the use of N-fertiliser affects the results for global warming, eutrophication and acidification substantially, as was shown in one of the scenario studies (number 4). The results for these impact categories are 15–26% lower when the amount of N is lowered to the yearly amount of N harvested. Reduction in the use of pesticide only effects terrestrial ecotoxicity.

'Transport of raw materials' is also an important process, but reduction of the transportation distance for raw materials only has a limited effect: The results for aquatic and sediment ecotoxicity are 1–7% lower when the transportation distance is halved (scenario study 1).

In the stage 'production of linoleum' the energy used while producing linoleum is the most important contributing process (Table 2). We expect that this data is valid and reliable. Therefore, saving on the use of electricity and gas at the factory site is also an important improvement opportunity for Forbo.

The sensitivity analysis showed that some aspects of linoleum composition can also have a considerable influence on the environmental profile for linoleum floors (scenario study 2). The contribution of pigments other than TiO_2 to all impact categories can be high, even though their mass share in the product is much lower (Fig. 3). However, the data on pigments were not provided by the suppliers of the pigments and the representativeness of these data might be disputed. There is a great variety of possible pigments, but little available information concerning their environmental performance. A more detailed analysis on this point focusing on the pigments that are actually used by Forbo, aimed at finding pigments that are the most environment-friendly, could lead to improvements in the future. The 2.0 mm gauge has a considerably better environmental performance than the 2.5 mm gauge, which is sold most frequently (Fig. 3). Since the actual life span of both floors is the same (although the technical life span might differ), Forbo might consider producing relatively more 2.0 mm products as a means of improving their environmental performance. Linoleum with tall oil has a better environmental profile than linoleum without tall oil, because the use of linseed is lower (Fig. 3). Therefore, a reduction in the amount of tall oil, in favour of linseed oil, is not advisable. Compared to the baseline 2.5 mm linoleum, cork linoleum produces better results in most categories, but performs considerably worse in others, especially the categories of abiotic depletion and odour (Fig. 3). Were the gas use during drying and milling of cork-granulate reduced, it would improve the results for these categories.

In the stage 'laying and use', the coal and oil used during the production of maintenance products is important. From the sensitivity analysis, it can be seen that the influence of maintenance in the 'use' phase is not negligible, as it is often thought to be (scenario study 1). In this study, the Swedish maintenance system, which was analysed as an alternative for the Dutch system, had an environmental profile which was 80–90% lower. However, this is at least partly due to a lack of data for the Swedish system. Therefore, no conclusions can be based on the comparison of these maintenance systems, other than that maintenance is not negligible. Better data on maintenance products is needed before more conclusions can be drawn on the influence of maintenance.

In the 'disposal' stage, the emissions produced during incineration are important. However, the 100% incineration of used linoleum and the linoleum waste is only an assumption. From the scenario analysis, it followed that the substitution of useful heat produced during the incinerating of linoleum with avoided electricity use shows the best environmental profile of all studied alternatives for handling waste (scenario study 3). Therefore, incineration seems a better alternative than landfill. However, this result should be considered with some care, because average ETH-data was used for landfills. These are probably not very realistic for the landfill of linoleum.

5.2 Advice for future studies on linoleum

From the sensitivity analysis (scenario study 5), it could be followed that the influence of capital goods and other data gaps (in this case small amounts of chemicals) can be substantial. According to a very rough scenario, leaving out capital goods may lead to an underestimation of 1–10% (toxicity not included). The influence of the missing chemicals could be even more substantial. According to a very rough scenario, these data gaps may lead to an underestimation of 5–40% (Table 3). Therefore, the results should not be used to compare systems with different capital goods or different maintenance systems.

More attention and effort to fill in data gaps, at least with rough estimations, is wanted. On the http://www.leidenuniv.nl/cml/lca2/index.html web site, a project is described to translate economic and environmental input/output data in such a way that they can easily be used in LCA. The first results of this project are presented in the form of interventions per dollar per sector.

It is also advisable to give the following topics extra attention in future studies on linoleum, as the data on these topics is fragmented and its influence on the environmental profile of linoleum could be considerable:

- The production and use of maintenance products, especially the Swedish type.
- The production and use of pigments other than TiO_2.
- Emissions of individual VOC at the factory site of Forbo.

5.3 Testing the new LCA guide

As mentioned in the introduction, this case study functioned as a 'test-case' for the updated LCA guide by Guinée et al. (2000). The study was carried out in the same period that the final decisions for the guide were made.

The test case resulted in some alterations in the sequence of steps in the guide, especially in the goal and scope and inventory phase. For example, the definition of system boundaries which ISO advises to treat in the goal and scope is treated in the inventory phase in the guide. This proved to be very feasible in the test case.

One of the advantages of the updated guide proved to be the structured interpretation analysis. By taking into consideration each step mentioned in the guide, the results are seen from all possible angles and this was very helpful to find the 'hotspots'. For instance, the sensitivity analysis carried out on cut-off processes and data gaps is something which is recommended in the guide, but often not done in LCAs. The results of this analysis showed a possible underestimation of up to 40%. This may change the conclusions drawn from a study and it underpins the guideline given in the guide to avoid cut-off whenever possible. However, all data that are not collected, but estimated must be carefully considered in the interpretation phase. As this case study shows, an estimation using a standard emission profile may not be representative and therefore may provide very odd results. This is a good example as to how inconsistencies can be discovered in every point of the interpretation analysis (LCA being an iterative process). Finally, this study shows that the role of sensitivity analysis can be very important in discovering improvement options for production processes.

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